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TURBULENT HEAT TRANSFER IN LARGE ASPECT CHANNELS, (U)
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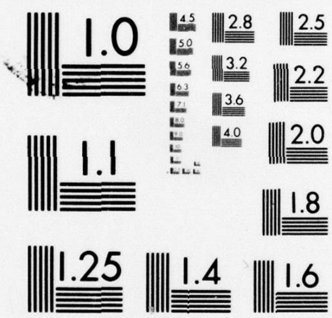

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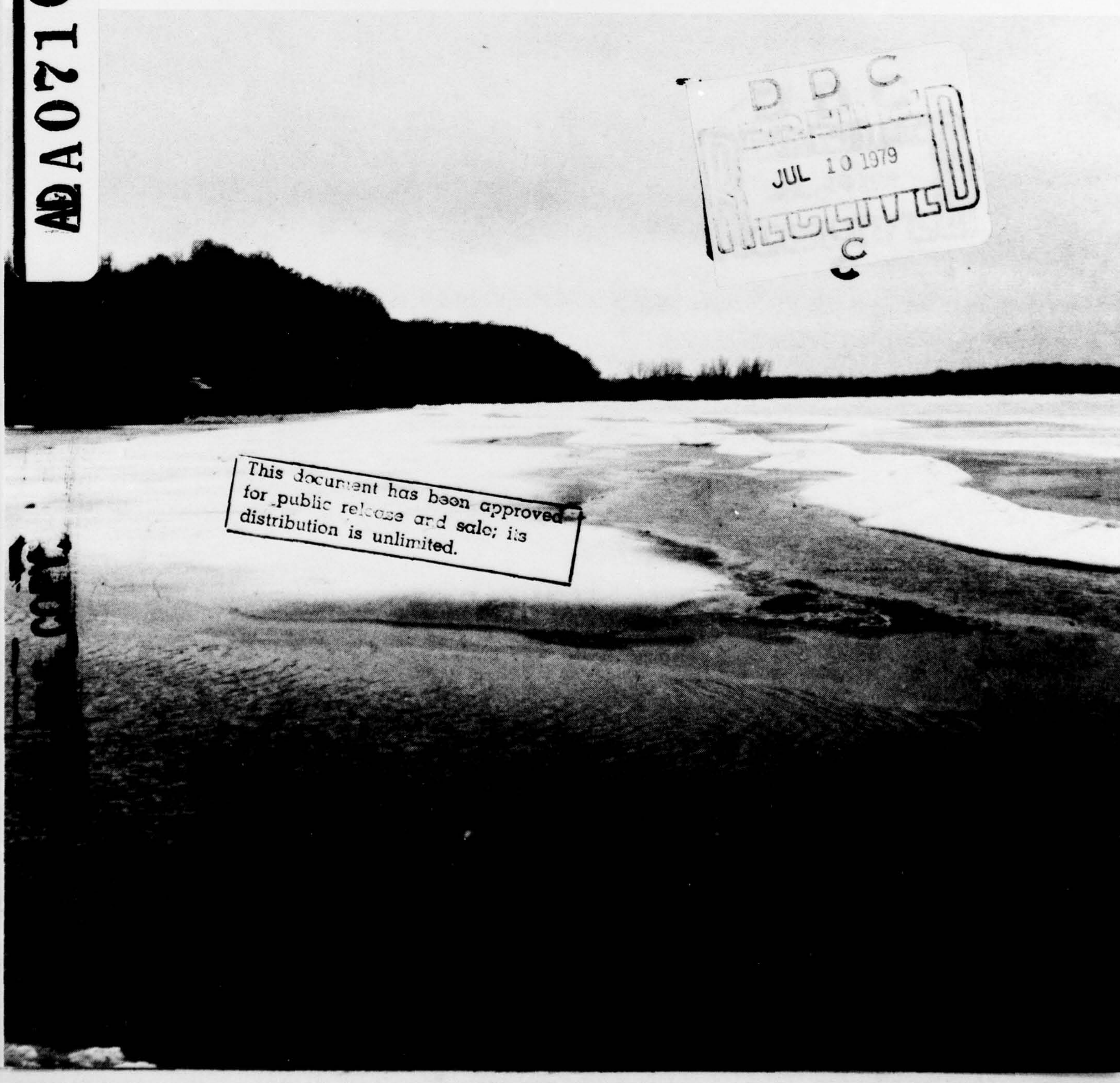

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Cover: Heat transfer from a river to its ice cover. (Photograph by George Ashton.)

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F.D. Haynes and G.D. Ashton

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Heat transfer in turbulent flow was measured in a rectangular channel with a width of 0.254 m and a flow depth of 0.0254 m. Correlations between the Nusselt and Reynolds numbers are given for a range of $3.02\times10^3 < Re < 2.236\times10^4$. A Prandtl number range of $9.90 \leq Pr \leq 12.28$ for water was used in the tests. The results are compared with those of other investigations and show that some well-known correlations underpredict the heat transfer by about 35%.

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PREFACE

This report was prepared by F.D. Haynes, Materials Research Engineer, of the Ice Engineering Research Branch, Experimental Engineering Division, and by Dr. G.D. Ashton, Chief, Snow and Ice Branch, Research Division, U.S.Army Cold Regions Research and Engineering Laboratory.

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Dr. Y.C. Yen and W.F. Quinn of CRREL reviewed the technical content of this report.

TURBULENT HEAT TRANSFER IN LARGE ASPECT CHANNELS

F.D. Haynes and G.D. Ashton

INTRODUCTION

Turbulent heat transfer in round tubes has been studied extensively and correlations between heat transfer and flow rate are well established. Turbulent heat transfer in rectangular channel geometries has been studied comparatively less. This study was motivated by the authors' interest in heat transfer from a river to its ice cover; the cross-section geometry of the river is better specified by an aspect ratio B/D where B is the channel width and D is the flow depth. This report presents new data for a closed channel flow with B/D = 10 and compares these data with the earlier data of Ashton (1971) and Hsu (1973). The data from the present study agree reasonably well with the predicted data of Petukhov and Popov (1963).

EXPERIMENTS

The experiments were conducted in a rectangular channel with width B = 0.254 m and flow depth D = 0.0254 m. A schematic of the apparatus is shown in Figure 1 and a cross-section schematic in Figure 2. The lower boundary of the apparatus was steel and enclosed a flow of trichloroethylene (TCE) circulated below the water channel at an inlet temperature of about -28 °C. The flow depth for the refrigerant was 0.0254 m. The top and sides of the water channel were constructed of wood and the entire channel section was insulated with urethane and fiberglass. The test section was 3.66 m long. At the inlet, a 4000-W immersion heater was controlled by a thermostat to allow control of the water temperature. The bulk temperature of the water flow was from about 3°C to 7°C. Water flow rates were from 0.64×10^{-3} to 4.5×10^{-3} $m^3 s^{-1}$ with corresponding mean flow velocities from 0.1 to 0.7 m s^{-1}. Temperatures of the water, wall, and refrigerant were measured at three stations. The distance from entry to the first station was 1.676 m. Based on the results of Hatton and Quarmby (1963), the first station was well beyond the distance at which entry effects are significant. The distance between stations was 0.9144 m. After flow adjustments were made, the system was allowed to stabilize for about 30 minutes before temperature data were collected.

Four thermistors, each calibrated at the water-ice triple point, were positioned (see Fig. 2) at each of the three stations and the thermistor signals were read with a Keithley Model 172 Digital Multimeter in a forward-reverse-forward sequence. Based on signal ranges used and manufacturer's specifications, absolute temperatures were determined to about 0.01°C and differential resolutions to about 0.005°C. The heat transfer rate was determined from measurements of the decrease in temperature of the flow between measuring stations with the heat flux assumed to be only from the flow to the bottom steel plate. This last assumption was verified by order-of-magnitude calculations. The experiments were also conducted at wall temperatures above 0°C so that no ice formed on the wall.

RESULTS

A total of 27 tests were conducted. The results are summarized in Table 1 in terms of the Prandtl number, Pr, Reynolds number, Re, and Nusselt number, Nu, defined, respectively, by

$$\mathrm{Pr} \equiv \frac{\mu C_p}{\rho} \qquad \mathrm{Re} \equiv \frac{U D_h \rho}{\mu} \qquad \mathrm{Nu} \equiv \frac{q D_h}{k(T_\infty - T_0)}$$

where U is the mean flow velocity, q is the heat flux from the flow to the wall, and $T_\infty - T_0$ is the difference between the bulk water temperature T_∞ and the wall temperature T_0. μ, ρ, k, and C_p are the dynamic viscosity, density, thermal conductivity, and specific heat capacity of the water and were

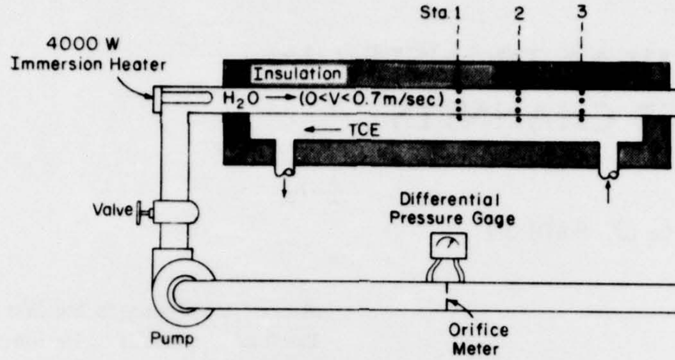

Figure 1. Apparatus schematic.

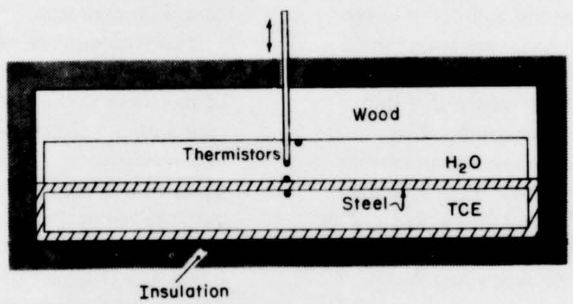

Figure 2. Cross-section schematic of apparatus.

Table 1. Summary of experimental results.

Test	T_∞ (°C)	*Pr*	*Re*	*Nu*
1	5.75	11.12	10380	137
2	4.80	11.47	12820	159
3	4.51	11.58	15020	186
4	4.48	11.59	17250	224
5	7.14	10.60	5055	104
6	6.08	11.01	6945	117
7	5.32	11.28	8070	137
8	5.74	11.14	9270	129
9	5.51	11.22	9270	189
10	4.74	11.50	10910	174
11	4.65	11.52	11565	142
12	4.56	11.56	12220	207
13	4.42	11.61	13325	236
14	4.95	11.42	14765	225
15	5.51	11.34	15070	256
16	5.23	11.30	16050	216
17	9.08	9.90	3490	103
18	4.62	11.60	3020	84
19	3.67	11.97	4055	83
20	3.50	12.05	4290	104
21	3.16	12.20	4745	92
22	2.98	12.28	5580	114
23	3.15	12.20	11960	193
24	3.06	12.26	16290	253
25	3.41	12.11	18550	249
26	4.02	11.81	20360	262
27	6.63	10.80	22360	289

Table 2. Summary of experimental results of Ashton (1971) and Hsu (1973)

Ashton (1971)

Test No	*Bulk water temperature °C*	*Rex10^{-4}*	*Pr*	*Nux10^{-2}*
1	2.36	7.31	12.60	6.93
2	2.90	6.91	12.34	6.83
3	0.98	6.40	13.23	6.56
4	2.32	8.83	12.60	7.87
5	1.71	8.77	12.88	8.59
6	0.65	8.45	13.39	7.89
7	0.43	8.43	13.49	9.04
8	0.24	8.32	13.59	8.16
9	0.25	10.61	13.58	8.99
10	0.25	5.57	13.58	7.09
11	0.30	17.60	13.56	14.53
12	1.03	3.41	13.21	3.47
13	0.40	11.89	13.52	10.27
14	1.00	4.51	13.23	4.67
Hsu (1973)				
1	0.29	17.97	13.57	14.40
2	0.29	17.97	13.57	15.83
3	1.00	2.14	13.23	2.42
4	2.00	2.14	12.75	2.47
5	0.43	8.56	13.49	8.13
6	0.15	8.56	13.62	7.09
7	0.87	3.57	13.28	3.72
8	1.41	2.85	13.04	3.16
9	0.27	19.24	13.57	14.14
10	0.40	3.57	13.52	3.75
11	0.93	1.069	13.26	1.33
12	0.41	9.98	13.52	8.43

evaluated at the bulk, or mixed flow temperature. The hydraulic diameter D_h is defined in the conventional way by $D_h = 4A/P$ where A is the cross-section area of the flow and P is the wetted perimeter. For the present experiments, $D_h = 1.818\ D$. All of the present experiments were in a narrow range of Prandtl number $9.90 \leqslant \mathrm{Pr} \leqslant 12.28$ with a representative Pr for most of the data of $\mathrm{Pr} \simeq 11.8$

Ashton (1971) and later Hsu (1973) investigated turbulent heat transfer at the bottom of an open channel flow in a flume 0.61 m wide and 12.2 m long; most experiments were conducted with a 0.15-m flow depth. They froze an ice slab onto the bottom of the flume and measured the heat flux by calculating the change in thickness of the ice at the center of the channel and well downstream from the inlet. Their test results are given in Table 2. In their experiments, $D_h = 2.667\ D_0$ where D_0 is the flow depth. In their experiments, the range of Prandtl number was quite small ($12.34 < \mathrm{Pr} < 13.62$) with a representative value of $\mathrm{Pr} \simeq 13.3$.

DATA INTERPRETATION

All the data are plotted in Figure 3 as a function of Re and Nu. Three of Hsu's data points overlap the data of the present study. For comparison, two analytical predictions are also plotted in Figure 3. The formula of Petukhov and Popov (1963) correlates turbulent heat transfer in round tubes quite well (±6%) for a wide range of Re and Pr [see, e.g., Karlekar and Desmond (1977, p. 351)] ; it underpredicts the Hsu (1973) and Ashton (1971) data by about 15%, and the data of the present study by about 35%. The formula of Petukhov and Popov (1963) is

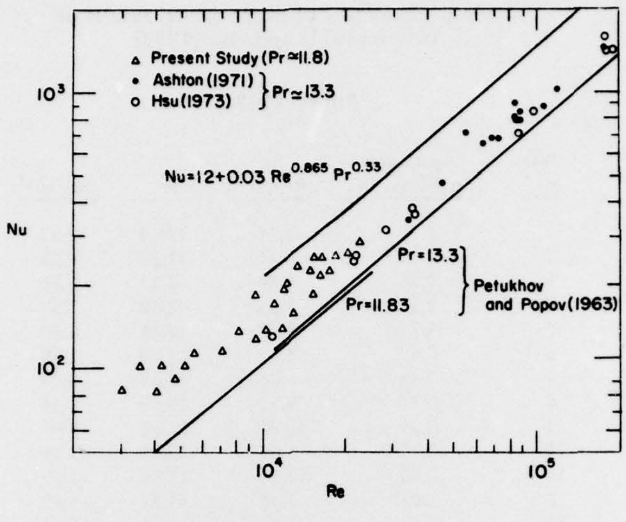

Figure 3. Heat transfer as a function of Reynolds number.

$$Nu = \frac{(f/8)\ Re\ Pr}{1.07+12.7\ (f/8)^{1/2}\ (Pr^{2/3}-1)} \tag{1}$$

where f has been calculated using the Filonenko equation [see Karlekar and Desmond (1977, p. 352)]

$$f = [1.82\ \log_{10} Re-1.64]^{-2} \tag{2}$$

We also note that the Petukhov-Popov formula yields Nusselt numbers somewhat greater (~20%) than the commonly used Dittus-Boelter equation or the Colburn equation in the range of Reynolds numbers of the Hsu and Ashton data sets.

Shibani and Ozisik (1977) presented an analytical solution for turbulent heat transfer between parallel plates with top and bottom cooling and correlated their analytical predictions in the range $0.1 < Pr < 10^4$ and $10^4 < Re < 10^6$ by

$$Nu = 12+0.03\ Re^{a_1}\ Pr^{a_2} \tag{3}$$

where

$$a_1 = 0.88 - \frac{0.24}{(3.6+Pr)} \tag{4}$$

$$a_2 = 0.33+0.5\ e^{-0.6Pr} \tag{5}$$

For the Prandtl numbers of the present data sets, the second term in eq 5 is negligible compared with the first. In eq 4, the second term is approximately -0.015 for the Prandtl numbers of the present data sets, so that the Shibani-Ozisik formula becomes

$$Nu = 12+0.03\ Re^{0.865}\ Pr^{0.33} \tag{6}$$

Equation 6 is also presented in Figure 3 and is seen to overpredict the Nusselt number by about 50%.

Several reasons are offered for the differences between the data and the predictions. First, it is difficult to achieve the idealized flow conditions implicit in the analyses. In particular, we suspect the steel plate had some roughness in the present experiments and in the Reynolds range of these experiments this could well have contributed to a higher Nusselt number. Second, the aspect ratio B/D_h varied from 1.5 for the Ashton-Hsu data sets to 5.4 for the present study, while the Petukhov-Popov formula is applicable to a round cross section roughly equivalent to a $B/D_h = 1$ and the Shibani-Ozisik formula is applicable to a $B/D_h = \infty$.

LITERATURE CITED

Ashton, G.D. (1971) The formation of ice ripples on the underside of river ice covers. Thesis presented to the University of Iowa, Iowa City, Iowa, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Hatton, A.P. and A. Quarmby (1963) The effect of axially varying and unsymmetrical boundary conditions on heat transfer with turbulent flow between parallel plates. *Int. J. Heat Mass Transfer*, vol. 6, p. 903-914.

Hsu, K. (1973) Spectral evolution of ice ripples. Thesis presented to the University of Iowa, Iowa City, Iowa, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Karlekar, B.V., and R.M. Desmond (1977) *Engineering heat transfer.* St. Paul: West Publishing Company, 580 p.

Petukhov, B.S., and V.N. Popov (1963) Theoretical calculation of heat exchange and frictional resistance in turbulent flow in tubes of an incompressible fluid with variable physical properties. *Trans. in High Temperature*, vol. 1, no. 1.

Shibani, A.A., and M.N. Ozisik (1977) A solution to heat transfer in turbulent flow between parallel plates. *Int. J. Heat Mass Transfer*, vol. 20, p. 565-573, May.

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